

Near-infrared Observations of Nova V574 Puppis (2004)

Sachindra Naik^{*}, D. P. K. Banerjee[†], N. M. Ashok[‡], & R. K. Das[§],

Astronomy and Astrophysics Division, Physical Research Laboratory, Navrangapura, Ahmedabad - 380009, Gujarat, India

Accepted for publication in MNRAS

ABSTRACT

We present results obtained from extensive near-infrared spectroscopic and photometric observations of nova V574 Pup during its 2004 outburst. The observations were obtained over four months, starting from 2004 November 25 (four days after the nova outburst) to 2005 March 20. The near-IR *JHK* light curve is presented - no evidence is seen from it for dust formation to have occurred during our observations. In the early decline phase, the *JHK* spectra of the nova are dominated by emission lines of hydrogen Brackett and Paschen series, OI, CI and HeI. We also detect the fairly uncommon Fe II line at $1.6872\ \mu\text{m}$ in the early part of our observations. The strengths of the HeI lines at $1.0830\ \mu\text{m}$ and $2.0585\ \mu\text{m}$ are found to become very strong towards the end of the observations indicating a progression towards higher excitation conditions in the nova ejecta. The width of the emission lines do not show any significant change during the course of our observations. The slope of the continuum spectrum was found to have a $\lambda^{-2.75}$ dependence in the early stages which gradually becomes flatter with time and changes to a free-free spectral dependence towards the later stages. Recombination analysis of the HI lines shows deviations from Case B conditions during the initial stages. However, towards the end of our observations, the line strengths are well simulated with case B model values with electron density $n_e = 10^{9-10}\ \text{cm}^{-3}$ and a temperature equal to $10^4\ \text{K}$. Based on our distance estimate to the nova of 5.5 kpc and the observed free-free continuum emission in the later part of the observations, we estimate the ionized mass of the ejecta to be between $10^{-5}\ M_\odot$ and $10^{-6}\ M_\odot$.

Key words: infrared: stars – novae, cataclysmic variables – stars: individual (V574 Pup)– techniques: spectroscopic

1 INTRODUCTION

V574 Pup was independently discovered to be in outburst by Tago (Nakano et al. 2004) on 2004 November 20.67 UT at $V \sim 7.6$ and, within a short time thereafter, by Sakurai on 2004 November 20.812 UT at $V \sim 7.4$ (Nakano et al. 2004). The follow-up observations reported by Samus & Kazarivets (2004) showed a post-discovery brightening before the onset of fading. Low dispersion optical spectra of the nova on 2004 November 21.75 UT showed $H\alpha$ and $H\beta$ emission lines with P Cygni components, along with the strong Fe II (multiplet 42) in absorption indicating that V574 Pup is a “Fe II” class nova near maximum light (Ayani 2004). Subsequent near-infrared spectroscopic observations of the nova on 2004 November 26.98 UT showed strong HI emission lines from the Paschen and Brackett series, OI lines at 1.1287 & $1.3164\ \mu\text{m}$ and a blend of NI & CI lines in the spectral

region 1.175 to $1.25\ \mu\text{m}$ (Ashok & Banerjee 2004). The optical spectra of the nova on 2004 November 26 and December 12 obtained by Siviero et al. (2005) were found to be dominated by Balmer hydrogen and FeII emission lines; no nebular lines were present in the spectra of December 12. One year after the outburst, the nova was found to be well into the coronal phase with the detection of [Si VI], [Si VII], [Ca VIII], [S VIII], and [S IX] lines in its spectrum (Rudy et al. 2005). Along with these lines, unidentified nova features at 0.8926 , 1.1110 , 1.5545 and $2.0996\ \mu\text{m}$ were also present in the spectrum. However, no evidence for emission from dust was seen in these observations.

V574 Pup was observed by the Spitzer Space Observatory one year after the outburst revealing strong coronal lines (Rudy et al. 2006). The spectroscopic observations by Lynch et al. (2007), three years after the outburst, showed the persistence of the coronal phase. Rudy et al. (2006) have remarked that the presence of strong coronal emission lines suggests similarity with a He/N nova. Siviero et al. (2005) have inferred that V574 Pup suffers negligible interstellar extinction though it is close to the galactic plane ($b = -2^\circ$).

^{*} snaik@prl.res.in

[†] orion@prl.res.in

[‡] ashok@prl.res.in

[§] rkdas@prl.res.in

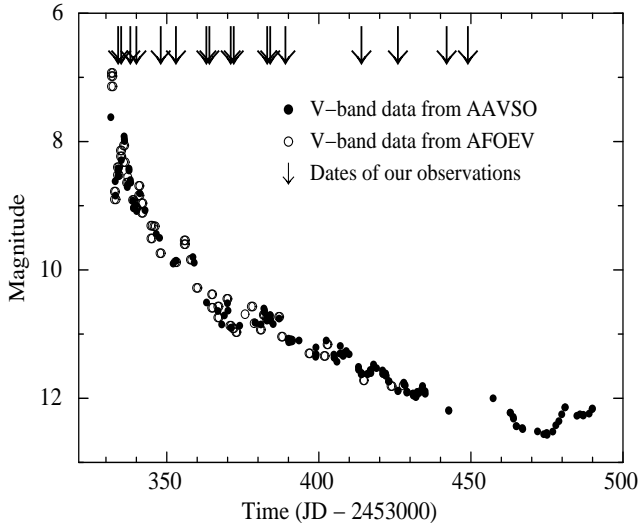


Figure 1. The V-band light curve of V574 Pup obtained from the AAVSO (shown by filled circles) and AFOEV data (shown by open circles). The arrow marks show the days of our near-infrared observations.

They estimate that the nova is located at very large distance of 15 to 20 kpc. In a later subsection we determine the distance to V574 Pup using the optical light curve and MMRD relation. V574 Pup is one of the novae detected with X-ray emission, among 12 classical novae studied by Ness et al. (2007) using Swift observations. It was observed on several occasions between 2005 May and 2005 August by Swift. The X-ray spectra showed it to be in the super soft X-ray phase. Ness et al. (2007) estimate the color excess $E(B - V) = 0.5$ and the distance to be 3.2 kpc.

2 OBSERVATIONS AND DATA REDUCTION

Near-infrared spectroscopic and photometric observations of V574 Pup were carried out fairly extensively using the 1.2-m telescope of the Mt Abu Infrared Observatory. The V band light curve is shown in Figure 1 with the epochs of our observations marked by arrows - the log of the observations is given in Table 1. The Mt. Abu spectra were obtained at a resolution of ~ 1000 using a Near-Infrared Imager/Spectrometer with a 256×256 HgCdTe (NICMOS3) array. Photometric observations of the nova were carried out on several nights (Table 1) in photometric sky conditions using the NICMOS3 array in the imaging mode. Several frames were obtained in four dithered positions, typically offset by ~ 30 arcsec from each other, with exposure times ranging from 0.4–100 s depending on the brightness of the nova. The sky frames were generated by median combining the average of each set of dithered frames and subsequently subtracted from the nova frames. A nearby field-star SAO 174367, observed at similar airmass as the nova, was used as the standard star for photometric observations. Aperture photometry was done using the APPHOT task in IRAF.

Spectral calibration was done using the OH sky lines that register with the stellar spectra. The spectra of the nearby field star SAO 174400 (1 Pup) were taken in *JHK* bands at similar airmass as that of V574 Pup on all the observation nights to ensure that the ratioing process (nova

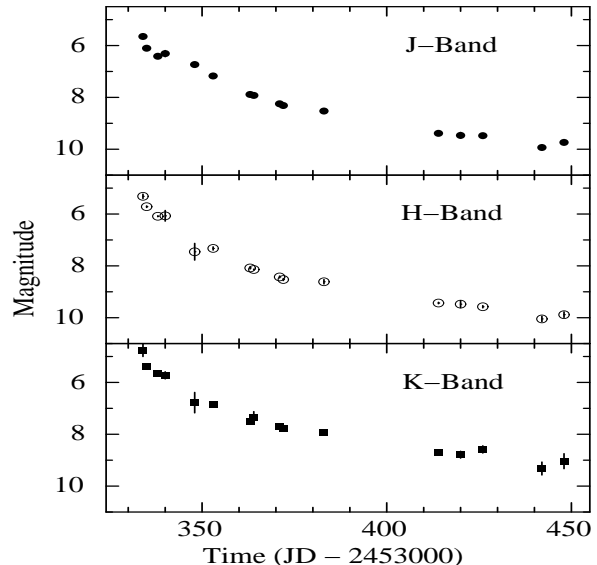


Figure 2. The light curves of V574 Pup in the *JHK* bands obtained from the Mount Abu Observatory. The *J*, *H* and *K* band light curves are shown in top, middle and bottom panels respectively.

spectrum divided by the standard star spectrum) removes the telluric lines reliably. 1 Pup, although an emission line star (spectral type A3 Iab), was chosen as the standard star due to its proximity to V574 Pup to minimise the effects of differential airmass between V574 Pup and the standard star. We have carefully removed the hydrogen lines in the spectra of 1 Pup ($\text{Pa}\beta$ and $\text{Br}\gamma$ were seen to be in emission; other Brackett lines are in absorption) before taking the ratios. The ratioed spectra were then multiplied by a blackbody curve corresponding to the standard star's effective temperature to yield the final spectra. Extraction and reduction of the spectra were done using IRAF tasks.

3 RESULTS AND DISCUSSION

3.1 Distance estimation from the visual light curve

We make a distance estimate to V574 Pup by analysing the V band light curve using archival data from the American Association of Variable Stars (AAVSO) and Association Francaise des Observateurs d'Etoiles Variables (AFOEV). The V band light curve is presented in Figure 1 with AAVSO data shown in filled circles and AFOEV data shown in open circles. The present light curve shows that the discovery of V574 Pup took place on its way to the maximum that was reached on 2004 November 22.2611. The pre-maximum brightening lasted for one day and subsequent to the maximum there was a sharp drop by about 2 magnitudes again within a day. Following this drop V574 Pup showed a relatively slower rise reaching $V=8.06$ on 2004 November 26.2458 and steadily decreased in brightness thereafter. For the purpose of calculation of t_2 and t_3 , the time for a decline of 2 and 3 magnitudes respectively, we assume that the sharp drop of 2 magnitudes lasting for a day can be

Table 1. Log of the Mt. Abu near-infrared observations of V574 Pup. The date of outburst is taken as 2004 November 20.67 UT.

Date of Observation	Days since outburst	Integration time (s)			Integration time (s)			Nova Magnitude		
		J-band	H-band	K-band	J-band	H-band	K-band	J-band	H-band	K-band
Spectroscopic Observations					Photometric Observations					
2004 Nov. 25	5	40	40	60	28	28	24	5.65±0.04	5.32±0.09	4.75±0.25
2004 Nov. 26	6	60	80	120	40	20	60	6.11±0.04	5.72±0.03	5.39±0.03
2004 Nov. 29	9	60	60	120	36	25	12	6.42±0.03	6.09±0.02	5.66±0.02
2004 Dec. 01	11	60	60	60	28	16	48	6.31±0.12	6.07±0.21	5.73±0.14
2004 Dec. 09	19	80	60	80	64	72	116	6.73±0.09	7.46±0.33	6.78±0.40
2004 Dec. 14	24	60	60	80	36	36	116	7.18±0.05	7.33±0.07	6.86±0.40
2004 Dec. 24	34	100	240	180	72	72	58	7.89±0.02	8.08±0.04	7.49±0.07
2004 Dec. 25	35	180	180	180	72	72	60	7.92±0.04	8.14±0.02	7.34±0.22
2005 Jan. 01	42	120	120	240	72	72	120	8.25±0.02	8.43±0.04	7.71±0.04
2005 Jan. 02	43	120	120	240	72	72	120	8.31±0.04	8.53±0.04	7.77±0.04
2005 Jan. 13	54	120	120	120	144	144	116	8.53±0.09	8.61±0.09	7.94±0.10
2005 Jan. 14	55	120	120	120	—	—	—	—	—	—
2005 Jan. 19	60	120	120	180	—	—	—	—	—	—
2005 Feb. 13	85	240	240	240	360	360	200	9.39±0.03	9.44±0.03	8.69±0.08
2005 Feb. 19	91	—	—	—	400	320	200	9.47±0.12	9.48±0.14	8.79±0.14
2005 Feb. 25	97	360	360	360	360	360	160	9.48±0.07	9.58±0.05	8.58±0.14
2005 Mar. 13	113	600	600	600	540	540	198	9.93±0.05	10.05±0.11	9.32±0.25
2005 Mar. 19	119	—	—	—	480	480	198	9.74±0.08	9.88±0.11	9.04±0.29
2005 Mar. 20	120	600	600	600	—	—	—	—	—	—

ignored and take $V_{max} = 6.93$ on 2004 November 22.2611 UT (JD 2453331.7611). We then derive from the V-band light curve a value of $t_2=10\pm1$ days and $t_3=25\pm2$ days. The absolute magnitude of the nova is then determined to be $M_V=-8.73$ using the maximum magnitude versus rate of decline (MMRD) relation of della Valle & Livio (1995). At maximum (JD 2453331.7611) AAVSO lists the B and V magnitudes as 7.79 and 6.93 respectively. The mean intrinsic color of novae at maximum is estimated to be $(B-V)_0 = +0.23\pm0.06$ (Warner 1995). Using this relation, we obtain $E(B-V) = 0.63$ and the extinction as $A_v=1.95$. We thus estimate the distance to V574 Pup to be $d=5.5$ kpc and adopt this value in future calculations. Ness et al. (2007) have derived a distance of 3.2 kpc which is closer to the value obtained in the present analysis compared to the 15 - 20 kpc estimate by Siviero et al. (2005). The significantly higher value for the distance estimated by Siviero et al. (2005) is due to the fainter value of V_{max} considered by them and also their assumption of a negligible interstellar extinction towards the nova.

3.2 JHK light curves of V574 Pup

The JHK light curves of V574 Pup, obtained from the present photometric observations are presented in Figure 2. A gradual fading is seen in all the three bands similar to the V band behavior. Further, no rise is seen in any of the near-IR bands indicating the absence of dust formation during the period of four months following the outburst. We note from the figure, and also from the data in Table 1, that the $(J-H)$ color index is generally found to be negative - specially so during the later stages of the observations. A negative $(J-H)$ index is characteristic of novae as shown by Whitelock et al. (1984). The reason for this is the presence of strong emission features in the J band spectra such as the

$\text{Pa}\beta$ and $\text{Pa}\gamma$, HeI 1.083 μm and the OI 1.1287 μm lines. As discussed in the following subsection, the HeI 1.083 μm and the OI 1.1287 μm lines are specially strong in V574 Pup giving rise to the observed behavior of the $(J-H)$ color index (the peak-to-continuum ratio of the HeI 1.083 μm line goes as high as ~ 150 in March 2005). However, it may be noted that a negative $(J-H)$ index is not expected if dust formation takes place (Whitelock et al. 1984; an example is the dust-forming nova V1280 Sco (Das et al. 2008)). The observed K band brightness of the nova is also affected by significant contributions from the HeI 2.0585 μm and Br γ lines.

3.3 Emission lines in the JHK spectra

The JHK spectra of V574 Pup are presented in Figures 3, 4 & 5, respectively. The early spectra cover the epoch of re-brightening seen at optical wavelengths and display typical emission lines of Paschen and Brackett series lines from hydrogen and the OI lines at 1.1287 μm and 1.3164 μm . Also seen prominently are lines of carbon and nitrogen, particularly in the J band. The details of the line identification are given in Table 2. The large observed ratio of the OI 1.1287 / 1.3164 μm lines indicates that Ly β fluorescence is the dominant process contributing to the strength of the 1.1287 μm line. The HeI line at 2.0581 μm is clearly detected in the K band spectra taken on November 29. This, and the J band HeI line at 1.0830 μm , gain in strength as the nova evolves. Their strength becomes comparable to hydrogen lines by 24-25 December and exceed them in strength by early January indicating a progress towards higher excitation conditions in the ejecta. Towards the end of our observations these HeI lines become very strong while other weaker He I lines at 1.7002 μm and 2.1120-2.1132 μm are also seen. We do not detect any coronal line features during the four months

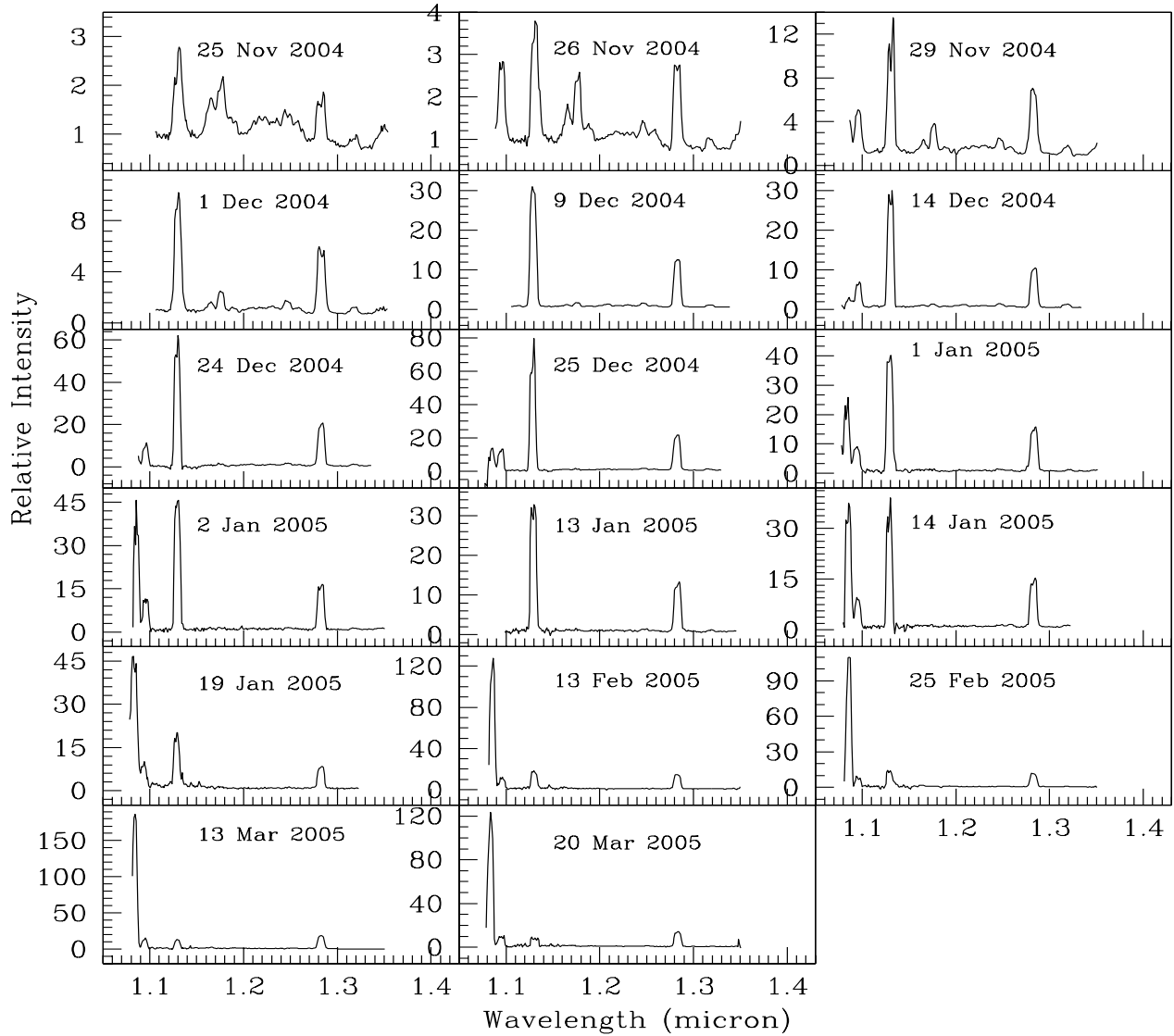


Figure 3. The *J*-band spectra of V574 Pup at different epochs with the continuum being normalized to unity at 1.25 μm .

of our observational campaign. As mentioned earlier, many coronal features were detected in V574 Pup one year after the outburst that were seen to last for the next two years (Rudy et al. 2005, Lynch et al. 2007).

During the course of our observations of V574 Pup, there were no significant changes seen in the width of the emission lines in the *J*, *H*, & *K* band spectra. This implies the absence of any significant change in the expansion velocity of the ejected envelope. In order to quantify the changes in the line widths in V574 Pup, the evolution of Brackett series lines which are prominent was investigated. The overall width of the hydrogen Brackett series emission lines did not change appreciably during the observations. The mean velocity of the expanding gas, from the Br lines, is estimated to be $1830 \pm 400 \text{ km s}^{-1}$ which agrees well with the findings

by Rudy et al. (2006) who determined an average velocity of 1800 km s^{-1} .

It is also noted that no lines from low ionization species like NaI or MgI are seen in the *JHK* spectra. These low ionization lines, which are indicative of low temperature conditions, have been suggested as potential diagnostic features to predict dust formation in the nova ejecta (Das et al. 2008). The absence of these lines in V574 Pup is consistent with the lack of dust formation in this nova. In this context, there is a line at $2.1452 \mu\text{m}$ which matches a NaI transition at that wavelength. However, for reasons discussed in Das et al. (2008), we are doubtful whether this line should be attributed to NaI. A notable feature in the *H* band spectra, is the structure of the Br11 line at $1.6806 \mu\text{m}$ which is seen to be distinctly different from other Brackett series lines in

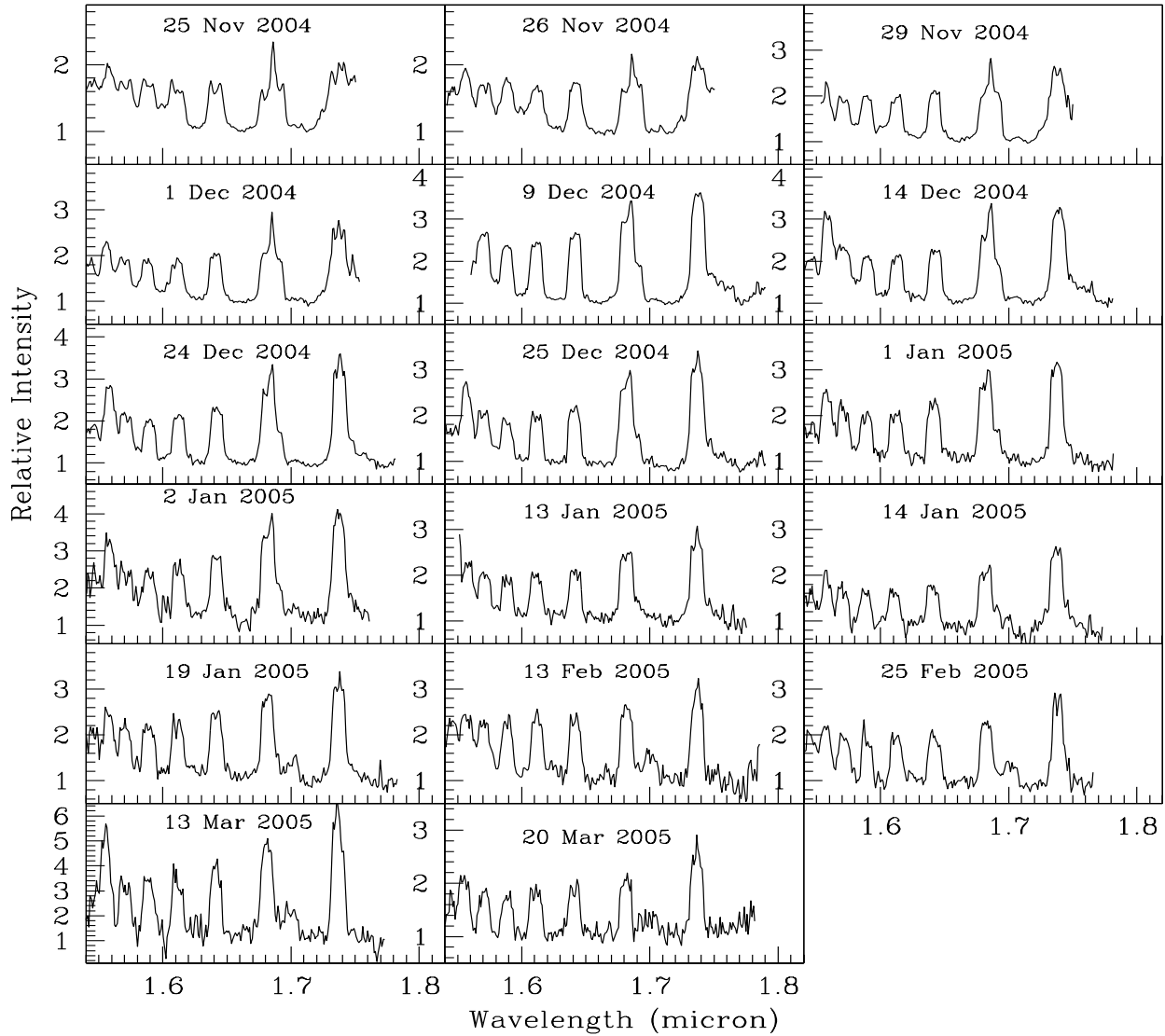


Figure 4. The H -band spectra of V574 Pup at different epochs with the continuum being normalized to unity at $1.65 \mu\text{m}$.

terms of both width and shape. This is most likely caused due to the blending of an additional nearby emission line of significant intensity. In the following subsection, we attempt to identify this additional line and show that it most likely is due to a FeII line at $1.6872 \mu\text{m}$.

3.4 Detection of the Fe II $1.6872 \mu\text{m}$ emission line in V574 Pup

We examine the distinct difference seen in the structure of Br11 line vis-a-vis other Br lines (Figure 4). This difference has persisted till the middle of 2005 January. The velocity of $3000 \pm 400 \text{ km s}^{-1}$ corresponding to the full width at half maximum (FWHM) of the Br11 line is larger than the average value of $1830 \pm 400 \text{ km s}^{-1}$ corresponding to other

Brackett series lines. This indicates that there is a definite contribution to Br11 line from an adjacent emission feature. It is noticed in the early spectra that there is a central enhancement (spike) in the Br11 line which gradually decreases in strength and by late 2004 December, Br11 line starts showing a prominent redward wing. Considering this behavior, we have looked for an emission line on the higher wavelength side of Br11. In two recent novae studied by us, namely, V2615 Oph (Das et al. 2009) and RS Oph (Banerjee et al. 2009) an emission line at $1.6872 \mu\text{m}$ has been clearly detected which is attributed to FeII. We suspect that this FeII line is present here too. To study the effect of this line on Br11, we have generated synthetic line profiles by adding two lines viz. a primary line centered at $1.6806 \mu\text{m}$ corresponding to Br11 and a second line at $1.6872 \mu\text{m}$ corre-

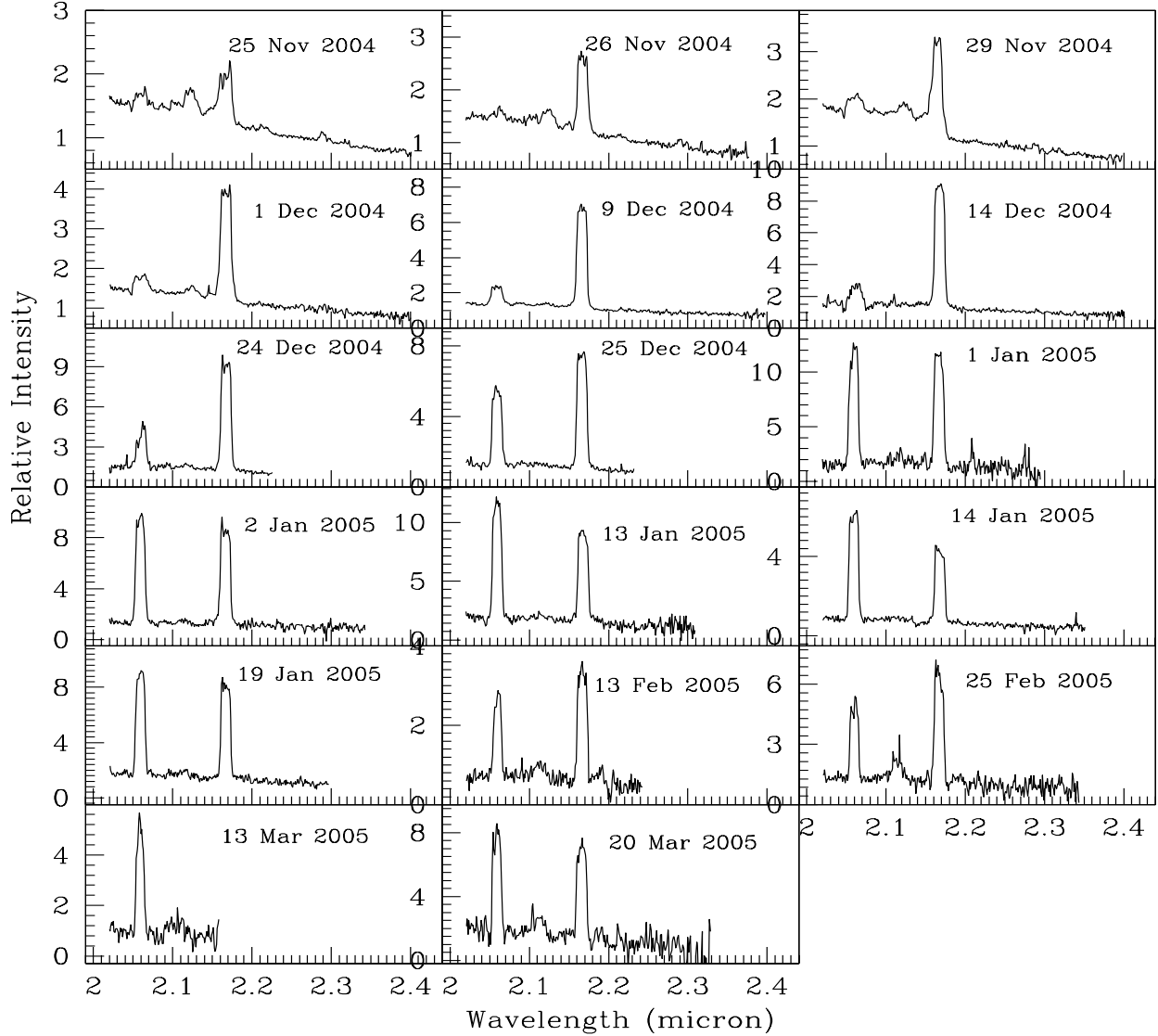


Figure 5. The K -band spectra of V574 Pup at different epochs with the continuum being normalized to unity at 2.2 μm .

sponding to FeII. Since there is no apriori knowledge on the shape of the FeII line, we assume that its shape can be simulated by the the Br12 line profile (we choose Br12 because it is free from blending with other lines). We have similarly assumed that Br11 is well simulated by the observed line profile of Br12 line. Keeping the peak intensity of synthetic Br11 line constant we have varied the intensity of the FeII line to simulate the observed temporal evolution. Two such synthetic spectra are shown in Figure 6. In the figure, we show the individual line profiles of Br11 and FeII with dotted lines and their resultant, co-added profile with a dashed line along with the observed profile (solid gray line). The left and right panels show the profiles for 2004 November 26 and 2004 December 9 respectively. The resultant and observed profiles are shown with some offset from the individ-

ual profiles for clarity. It is seen that the synthetic profiles resulting from the combination of Br11 and Fe II match the observed line profile reasonably well. This indicates that the Fe II 1.6872 μm line is present in V574 Pup. Based on the work of Banerjee et al. (2009), another Fe II line at 1.7413 μm could also be expected in the spectrum. It is possible that this line is also there, but it is difficult to draw a definitive conclusion regarding its presence since it could be blended, rather too closely with Br10 and also a cluster of CI lines in the 1.74-1.77 μm region. We note that these FeII lines are not too commonly reported in the spectra of novae. Apart from V2615 Oph (Das et al. 2009) and RS Oph (Banerjee et al. 2009), there are two more novae, namely V2540 Ophiuchi (Rudy et al. 2002) and CI Aquila (Lynch et al. 2004) where these lines appear to be detected. The ex-

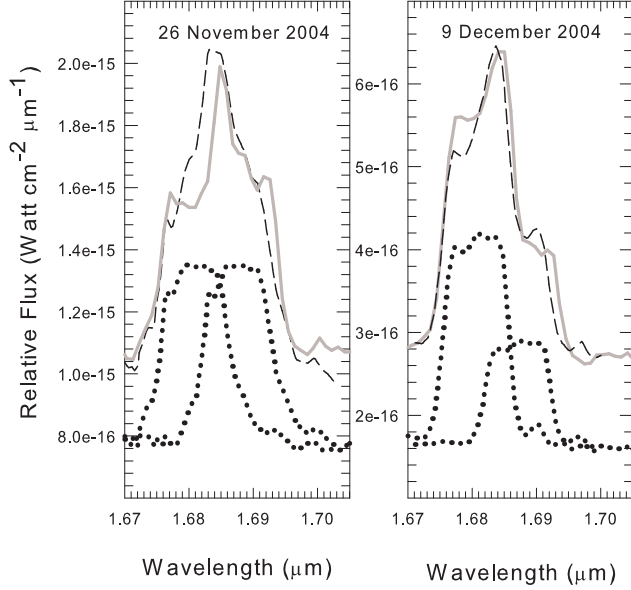


Figure 6. The profiles of Br11 line at 1.6806 μm (dotted line), Fe II line at 1.6872 μm (dotted line), the added line (Br11+Fe II) intensity (dashed line) and the observed data (gray solid line) are shown for 2004 November 26 (left panel) and for 2004 December 9 (right panel). The intensity of the Fe II line was adjusted to match the co-added profile with the observed profile. The co-added and observed profiles are shown with some offset in order to make it clear for comparison.

citation mechanism for these lines is believed to be Lyman α and Lyman continuum fluorescence coupled with collisional excitation (Banerjee et al. 2009 and references therein).

3.5 Evolution of the continuum

We analyse and discuss the evolution of the continuum spectra of V574 Pup here. At the time of outburst, a nova's continuum is generally well described by a blackbody distribution from an optically thick pseudo-photosphere corresponding to a stellar spectral type A to F (Gehrz 1988). The spectral energy distribution then gradually evolves into a free-free continuum as the optical depth of the nova ejecta decreases (Ennis et al. 1977; Gehrz 1988). The evolution of the continuum of V574 Pup is shown in Figure 7 wherein we have shown representative spectra sampling the duration of our observations. The spectra in Figure 7 were flux calibrated using the broadband *JHK* photometric observations presented in Table 1. During this process of calibrating the flux in the continuum, we note that the observed broadband flux is a sum of contributions from both the continuum and also from emission lines. As the emission lines of H I, O I and He I are strong and contribute significantly to the broadband fluxes, we have first calculated the contribution of all the prominent emission lines to the observed spectra and removed this contribution from the broad band photometric fluxes measured from the *JHK* photometry. This gives the true continuum flux which was used to calibrate the spectra in Figure 7.

Table 2. List of prominent lines in the *JHK* spectra

Wavelength (μm)	Species	Remarks
1.0830	He I	
1.0938	Pa γ	
1.1287	O I	
1.1600 - 1.1674	C I	strongest lines at 1.1653, 1.1659, 1.16696 μm
1.1748 - 1.1800	C I	strongest lines at 1.1748, 1.1753, 1.1755 μm
1.1819 - 1.1896	C I	strongest lines at 1.1880, 1.1896 μm
1.2187 - 1.2382	C I, N I	blend of N I 1.2187, 1.2204, 1.2329, 1.2382, & C I 1.2249, 1.2264 μm
1.2461, 1.2469	N I	
1.2562 - 1.2614	C I	blend of C I 1.2562, 1.2569, 1.2601, 1.2614 μm
1.2818	Pa β	
1.3164	O I	
1.5439	Br 17	
1.5557	Br 16	
1.5685	Br 15	
1.5881	Br 14	
1.6005	C I	may be present
1.6109	Br 13	
1.6407	Br 12	
1.6806	Br 11	
1.6872	Fe II	
1.7002	He I	
1.7045	C I	
1.7362	Br 10	
1.74 - 1.77	CI	blend of several C I Lines
2.0585	He I	
2.1120, 2.1132	He I	
2.1156 - 2.1295	C I	blend of several C I lines, strongest being 2.1156, 2.1191, 2.1211, 2.1260, 2.1295 μm
2.1452	Na I?	
2.1655	Br γ	
2.2156-2.2167	C I	blend of C I lines at 2.2156, 2.2160, 2.2167 μm
2.2906	C I	

We have tried to fit the spectra in Figure 7 with power law fits i.e. $F_\lambda \propto \lambda^{-\alpha}$. In the beginning of our observation i.e. on 2004 November 25 (4 days after outburst) and 2004 December 01, the continuum spectrum approximately fits a spectral index of $\alpha \sim 2.75$. A blackbody fit, expected to have an index of $\alpha = 4.0$ at longer wavelengths, does not simulate the data too well. The subsequent spectra gradually become flatter with a slope of $\alpha \sim 2.0$ on 2004 December 14. The nova continuum is subsequently found to become flatter with time and gradually match a free-free emission spectrum towards the end of our observation campaign. The spectrum of 2005 February 25 in Figure 7 has been fit with a free-free spectrum computed at a temperature of $T = 10^4$ K.

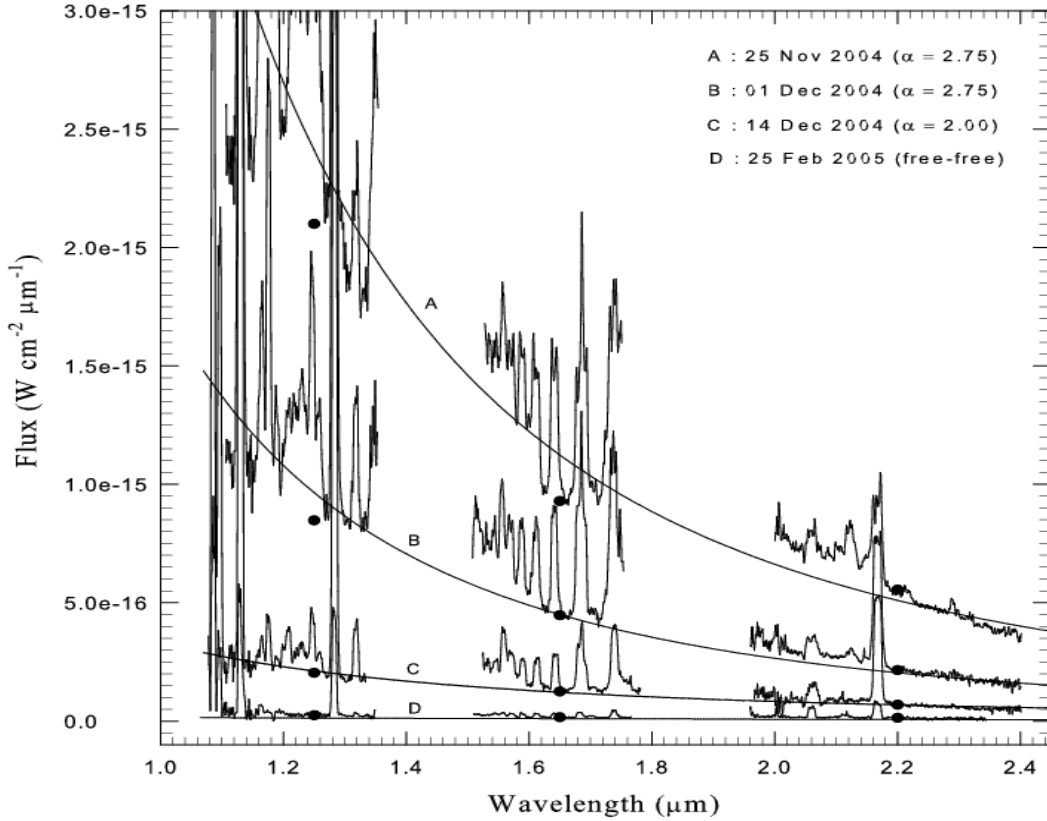


Figure 7. The composite *JHK* spectra of V574 Pup for 25 November 2004 (A), 1 December 2004 (B), 14 December 2004 (C), and 25 February 2005 (D) from near-infrared observations with the Mt Abu telescope. Model fits to the data (using either a power law or a free-free spectral dependence) are shown by the continuous lines; the broadband fluxes (corrected for contribution from line emission - see text) are shown by filled circles. The slope of the continuum spectra of A, B, and C are compared with power law fits ($F_{\lambda} \propto \lambda^{-\alpha}$) with slopes $\alpha = 2.75, 2.75$ and 2.0 , respectively. A free-free emission function at temperature 10^4 K is plotted along with the fourth spectrum (noted as D). It appears that the nova continuum has flattened gradually to a free-free type of emission towards the end of our observations.

3.6 Case B recombination analysis

The recombination case B analysis for the HI lines were carried out for all the observed spectra and the representative results for five epochs covering the first 80 days of our observations are shown in Figure 8. We have plotted in Figure 8 the observed relative strength of Brackett series lines with the line strength of Br12 as unity along with the predicted values for three different recombination case B emissivity values from Storey & Hummer (1995). These predicted values cover a representative temperature of $T = 10^4$ K and the

electron densities of $n_e = 10^9 \text{ cm}^{-3}$, 10^{10} cm^{-3} and 10^{12} cm^{-3} . High electron densities are considered because the ejecta material is expected to be dense in the early stages after the outburst. For the early epochs, namely 2004 November 25 and 2004 December 1, the Br10 line is not included as it is at the edge of the observed spectra and not adequately covered. The errors in the estimated line strengths are $\sim 10\%$ for the Br γ , Br12 & Br13 lines and $\sim 20\%$ for the Br14, Br15, Br16 & Br17 lines. The errors for the Br11 line are $\sim 30\%$ for 2004 November 25, $\sim 20\%$ for 2004 December

1 and $\sim 10\%$ for observations on the other days. The variable error assigned to the Br11 is due to the presence of a Fe II line at $1.6872 \mu\text{m}$ that was strong in the initial phase of our observations, gradually weakened and finally became undetectable.

Figure 8 shows that the observed line intensities clearly deviate from case B values in the initial phase of our observations. Specifically, Br γ which is expected to be the relatively stronger than the other Br lines, is observed to be considerably weaker in the early observations. This is most likely due to optical depth effects in the Brackett lines (Lynch et al 2000). Such deviations from the recombination case B conditions during the early stages after outburst can be expected and have been observed in other novae too, for example, V2491 Cyg and V597 Pup (Naik et al. 2009), RS Oph (Banerjee et al. 2009) etc. However, towards the end of the observations, on 2005 February 13 and 25 (fourth and fifth panels of Figure 8) there is an indication that Case B conditions have begun to prevail. For these last two dates, it is found that the observed data matches well with the predicted values for the recombination case B values of $T = 10^4 \text{ K}$ and an electron density in the range $n_e = 10^9 - 10^{10} \text{ cm}^{-3}$.

3.7 Estimation of the mass of the nova ejecta

We estimate the mass of the ionized gas in the ejecta using the fact that on 2005 February 25, the observed SED of V574 Pup is well fit by a free-free flux distribution at a temperature of $T = 10000 \text{ K}$ (Figure 7).

The free-free volume emission coefficient from an ionized gas is given by

$$j_{\lambda\text{ff}} = 2.05 \times 10^{-30} \lambda^{-2} z^2 g T^{-1/2} n_e n_i e^{(-c_2/\lambda T)} \text{ W cm}^{-3} \mu\text{m}^{-1}$$

where λ is the wavelength in μm , z is the charge, g is the Gaunt factor (assumed equal to unity), T is the temperature, n_e and n_i are the electron and ion densities respectively and $c_2 = 1.438 \text{ cm K}$. The total continuum emission from the nova ejecta can then be estimated by multiplying the flux given in the above equation with the shell volume V_s and equating it to the observed flux $F_{\lambda\text{ff}}$ which equals:

$$F_{\lambda\text{ff}} = j_{\lambda\text{ff}} \times V_s / 4\pi d^2$$

where d is the distance to the object. We use $d = 5.5 \text{ kpc}$, $T = 10^4 \text{ K}$ and $n_e = n_i$ assuming a pure and completely ionized hydrogen ejecta ($z = 1$). At K band center ($\lambda = 2.2 \mu\text{m}$), using the observed flux on 2005 February 25 to be $1.325 \times 10^{-17} \text{ W cm}^{-2} \mu\text{m}^{-1}$ and $n_e = 10^{10} \text{ cm}^{-3}$ derived from the recombination analysis, we obtain the volume of the emitting HI gas to be $V_s = 2.2 \times 10^{41} \text{ cm}^3$. Similar values for V_s are obtained if the J and H band observed fluxes and corresponding central wavelengths of these bands are used instead.

The mass of the ionized gas can then be calculated using $M_{\text{gas}} = V_s n_e m_H$, where m_H is mass of the hydrogen atom. Taking $n_e = 10^{10} \text{ cm}^{-3}$ gives a value of $M_{\text{gas}} = 1.8 \times 10^{-6} M_\odot$. A similar calculation for $n_e = 10^9 \text{ cm}^{-3}$, which could also be a valid estimate in V574 Pup (as indicated from case B analysis for 25 Feb 2005), yields $M_{\text{gas}} = 1.8 \times 10^{-5} M_\odot$. Thus, within the uncertainties associated with the parameters involved, we would estimate the mass of the ionized gas to be in the range of 1.8×10^{-5} to $1.8 \times 10^{-6} M_\odot$. This estimate is reasonably in agreement with the observed range of the mass

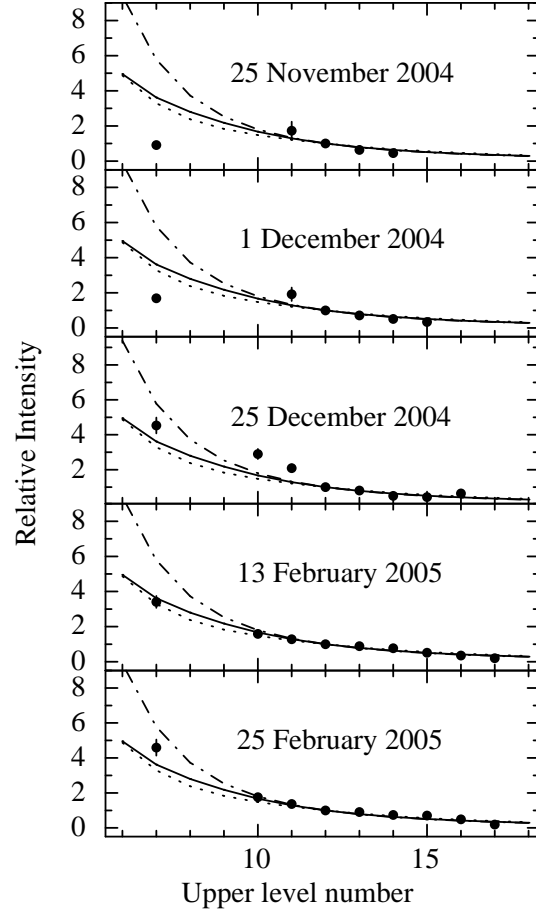


Figure 8. Recombination analysis for the hydrogen Brackett lines in V574 Pup on selected dates of our near-IR observations (as noted in the figure). The abscissa is the upper level number of Brackett series line transition. The line intensities are relative to that of Br 12 which is normalized to unity. The errors in the estimated line strengths are $\sim 10\%$ for the Br γ , Br12 & Br13 lines and $\sim 20\%$ for the Br14, Br15, Br16 and Br17 lines. The errors for the Br11 line are $\sim 30\%$ for 2004 November 25, $\sim 20\%$ for 2004 December 1 and $\sim 10\%$ for observations on the other days. The case B model predictions for the line strengths are also shown for a temperature $T = 10^4 \text{ K}$ and electron densities of $n_e = 10^{12} \text{ cm}^{-3}$ (dot-dash line), 10^{10} cm^{-3} (solid line), and 10^9 cm^{-3} (dotted line).

of novae ejecta (1 to $30 \times 10^{-5} M_\odot$) and also the theoretically calculated range of 5.3×10^{-8} to $6.6 \times 10^{-4} M_\odot$ in the extended grid of models computed by Yaron et al. (2005).

The mass estimate made above can be checked for consistency through an alternative approach. As discussed in section 3.6, on 13 and 25 February 2005 there is a reasonably good match between the observed line intensities of HI Brackett series lines with the theoretical case B values listed in Storey and Hummer (1995) for $T = 10^4 \text{ K}$ and $n_e = 10^9 - 10^{10} \text{ cm}^{-3}$. For these values, the emissivity in Br γ is expected to be $j(\text{Br}\gamma) \sim 4.5 \times 10^{-14} \text{ W cm}^{-3}$ (Storey and Hummer, 1995). From the observed data of 2005 February 13 and 25, the Br γ line is measured to have a mean line luminosity of $\sim 5.0 \times 10^{-19} \text{ W cm}^{-2}$. Using $d = 5.5 \text{ kpc}$, the total power in the line is thus $1.8 \times 10^{28} \text{ W}$. With $j(\text{Br}\gamma)$ as estimated above, this yields the volume of the emitting gas to be $V_s = 4.0 \times 10^{41} \text{ cm}^3$ (consistent with the value

of $2.2 \times 10^{41} \text{ cm}^3$ derived from the free-free analysis) which thereby leads to a similar mass estimate as made earlier.

4 SUMMARY

We have presented an extensive set of spectroscopic and photometric observations of nova V574 Puppis. From the V band light curve the distance to the nova is estimated to be ~ 5.5 kpc. The near-IR light curve shows a steady decline with time without any evidence for the buildup of an infrared excess associated with dust formation in the ejecta. However, an infrared excess at longer wavelengths can not be ruled out. Along with lines of hydrogen, helium, oxygen and carbon, we also detect the Fe II emission line at $1.6872 \mu\text{m}$ in the near-IR spectra. The nova continuum is modeled and found to evolve from a $\lambda^{-2.75}$ dependence to a free-free emission during the period of our observations. A recombination analysis of the HI lines is presented. We estimate the mass of the ionized gas in the ejecta and show it to lie in the range $10^{-5} M_{\odot}$ and $10^{-6} M_{\odot}$.

ACKNOWLEDGMENTS

We wish to thank the referee Prof. A Evans for his useful suggestions on the paper. The research work at Physical Research Laboratory is funded by the Department of Space, Government of India. We thank George Koshy for help with some of the observations. We acknowledge with thanks the variable star observations from the AAVSO International Database, contributed by observers worldwide, and used in this research. This research has made use of the AFOEV database, operated at CDS, France.

REFERENCES

- Ashok, N. M., Banerjee, D. P. K., 2004, IAU Circ., 8447, 4
 Ayani, K. 2004, IAU Circ., 8443, 2
 Banerjee, D. P. K., Das, R. K., Ashok, N. M., 2009, MNRAS, 399, 357
 Das, R. K., Banerjee, D. P. K., Ashok, N. M., Chesneau, O., 2008, MNRAS, 391, 1874
 Das, R. K., Banerjee, D. P. K., Ashok, N. M., 2009, MNRAS, 398, 375
 della Valle, M., Livio, M., 1995, ApJ, 452, 704
 Ennis, D., Beckwith, S., Gatley, I., Matthews, K., Becklin, E. E., Elias, J., Neugebauer, G., Willner, S. P., 1977, ApJ, 214, 478
 Gehr, R. D., 1988, ARA&A, 26, 377
 Lynch D.K., Rudy R.J., Mazuk S., Puetter R.C., 2000, ApJ, 541, 791
 Lynch, D. K., Wilson, J. C., Rudy, R. J., Venturini, C., Mazuk, S., Miller, N. A., Puetter, R. C., 2004, AJ, 127, 1089
 Lynch, D. K., Rudy, R. J., Prater, T. R., Gilbert, A. M., Mazuk, S., Perry, R. B., Puetter, R. C., 2007, IAU Circ., 8906, 1
 Naik, S., Banerjee, D. P. K., Ashok, N. M., 2009, MNRAS, 394, 1551
 Nakano, S., Tago, A., Sakurai, Y., Kushida, R., Kadota, K., 2004, IAU Circ., 8443, 1
 Ness, J.-U., Schwarz, G. J., Retter, A., Starrfield, S., Schmitt, J. H. M. M., Gehrels, N., Burrows, D., Osborne, J. P., 2007, ApJ, 663, 505
 Rudy, R. J., Lynch, D. K., Mazuk, S., Venturini, C. C., Puetter, R. C., Perry, R. B., 2002, AAS, 201, 4006
 Rudy, R. J., Lynch, D. K., Mazuk, S., Venturini, C. C., Puetter, R. C., Perry, R. B., Walp, B., 2005, IAU Circ., 8643, 2
 Rudy, R. J. et al., 2006, AAS, 209, 906
 Samus, N. N., Kazarovets, E., 2004, IAU Circ., 8445, 2
 Siviero, A., Munari, U., Jones, A. F., 2005, IBVS, 5638, 1
 Storey, P. J., Hummer, D. G., 1995, MNRAS, 292, 41
 Warner, B., 1995, *Cataclysmic Variable Stars. Cambridge Astrophysics Series*, Cambridge Univ. Press, Cambridge, New York
 Whitelock, P. A., Carter, B. S., Feast, M. W., Glass, I. S., Laney, D., Menzies, J. W., Walsh, J., Williams, P. M., 1984, MNRAS, 211, 421
 Yaron, O., Prialnik, D., Shara, M. M., Kovetz, A., 2005, ApJ, 623, 398